Heat transfer from a horizontal bundle of tubes in an air fluidized bed
by Stephen John Priebe

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Chemical Engineering
Montana State University

Abstract:
Heat transfer from a horizontal bundle of bare tubes to a fluidized bed was measured to determine; 1) effect of number of tubes in a tube bundle, and 2) effect of heater position in a 19 tube bundle. Glass beads were used for the particle bed, and air was the fluidizing media.

Results indicated that, at higher air flowrates, the heat transfer increased with number of tubes up to about 7 tubes, and then decreased. At lower flowrates, the heat transfer increased monotonically over the range investigated.

Results also showed that heat transfer was less in the center of a tube bundle, with a symmetrical bundle. Some indication was given that nearby heaters may have an adverse affect on the heat transfer. This was shown in asymmetrical bundles where the lowest heat transfer did not occur in the center.

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Signature Stephen John Pinch

Date May 29, 1973

HEAT TRANSFER FROM A HORIZONTAL BUNDLE OF TUBES IN AN AIR FLUIDIZED BED

by

STEPHEN JOHN PRIEBE

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ABSTRACT

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INTRODUCTION

Fluidization of a bed of particles implies that the particles are suspended in some fluid (gas or liquid) moving upward through the bed. The degree of fluidization depends upon the velocity of the fluidizing medium. When the velocity is such that the pressure drop across the bed is equal to the weight of the bed, fluidization occurs. This point is known as minimum fluidization. At minimum fluidization, particle circulation is limited, and the bed of particles acts like a highly viscous fluid.

As the velocity is increased, the particles begin to circulate in a regular manner, rising in the center, and falling at the sides of the column. Further increase in the velocity, causes bubbles to form. The size of the bubbles depends upon the nature of the distributor plate, and the gas velocity. This regime of flow is known as aggregative fluidization.

With increased velocity, the bubbles begin to coalesce until "slugs" of gas, occupying the entire crossection of the column, pass through the bed. This is known as slugging. These three regimes of fluidization are sketched in Figure 1.

Fluidization has been used commercially for about thirty years. It was initiated primarily by the petroleum industry, in the fluidized catalytic cracking units. Two primary advantages over the former fixed bed reactors, are better contact and continous regeneration of catalyst.

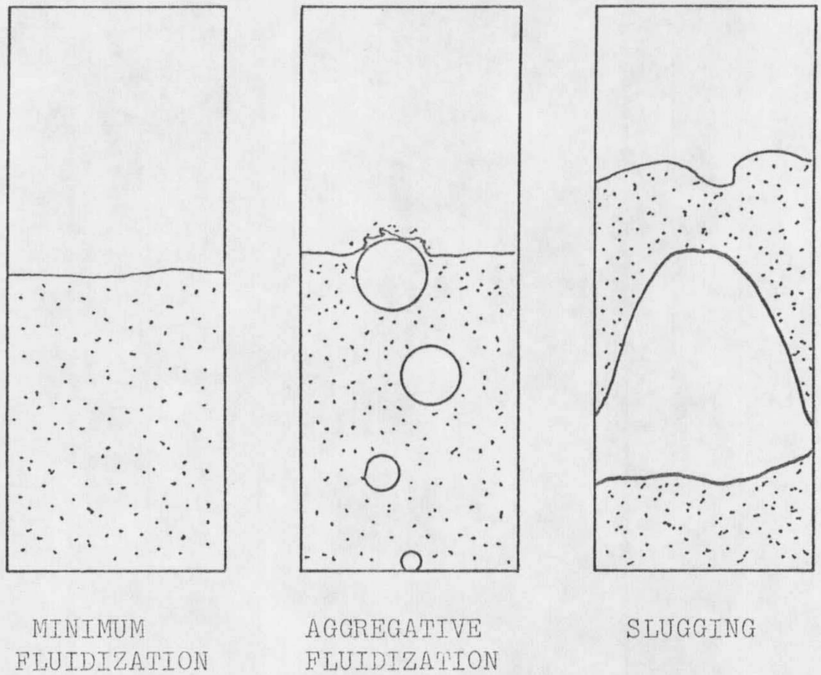

Figure 1. Regimes of Fluidization

From these beginnings, fluidization spread to many other areas such as roasting of metal ores, drying of some powders, and treating of radioactive wastes from nuclear reactors. In all of these applications, and many more, heat must be transferred to the bed.

Originally, this heat transfer was done simply by heating the walls of the column. As fluidized beds got larger, this became unsatisfactory, so people turned to internal heating. This is usually accomplished with vertical or horizontal tube bundles. The fluidized bed greatly increased the heat transfer coefficients over those obtained from forced convection alone. This is attributed to the much higher degree of turbulence in the bed, and to the large amount of particle contact with the heat transfer surface.

Work has been done to determine the effect of various properties of the bed particles, and the fluidizing media on the heat transfer coefficients. The purpose of this study is to determine how the heat transfer coefficient in a horizontal bundle of tubes is affected by the size of the tube bundle, and by the position of a heater in the bundle.

THEORY AND RELATED STUDIES

The theory and related studies will be discussed in two parts as follows:

1) Mechanism of heat transfer

2) Effect of various parameters on heat transfer coefficients.

Mechanism of Heat Transfer.

Several models for heat transfer to a bed of fluidized particles have been proposed to account for the large heat transfer coefficients observed experimentally.

In 1949 and 1954, two similar models were proposed by Leva, Weintraub, and Brummer (5), and Levenspiel and Walton (6), respectively. This model proposed that the boundary layer on the surface of the heater is eroded away by the action of the particles moving past the surface. This reduction in film thickness would decrease the resistance, and so increase the heat transfer coefficient.

Another model, proposed by Mickley and Fairbanks (6) in 1955, suggests that a "packet" of particles from the bulk phase comes into contact with the heating surface. After remaining there only a short time, the "packet" moves back into the bulk phase where it is quickly disperesed, thus circulating the heat rapidly.

The third model, proposed by Ziegler, Koppel, and Brazelton (13), and modified by Genetti and Knudsen (3), and again by Bartel (1), views the mechanism as occurring with single particles. A particle moves into the region near the heating surface,but rather than being heated by direct contact with the heater, it is surrounded by gas at the temperature of the heater. Because of the larger surface area exposed, the particle is rapidly heated and then moves back into the bulk phase, where the heat is dispersed.

Using this particle model, Ziegler, et al found that the particle Nusselt number can be expressed as:

$$Nu_p = \frac{7.2}{\left(1 + \frac{6k_{air}\bar{t}}{\rho_s C_{ps} D_p^2}\right)^2}$$

where,

k_{air} = thermal conductivity of fluidizing air, BTU/hr-ft-°F

ρ_s = density of particles, lb/ft^3

$\bar{t}$ = mean residence time, hr

C_{ps} = heat capacity of solid particles, BTU/lb-°F

D_p = particle diameter, ft

Genetti and Knudsen found, from their study, that the constant 7.2, should be replaced by $5(1-\epsilon)^{0.5}$, where $(1-\epsilon)$ is the particle fraction is the bed. Bartel further extended the model to account for tube spacing in a bundle, and for fin height in cases where finned tubes are used. Zigler and Brazelton (14) showed, by comparing mass transfer and heat transfer rates, that a particle mode mechanism accounts for 80-95% of the total heat transfer from the heating surface to the bed.

Effect of Various Physical Parameters on Heat Transfer Coefficients

The physical parameters effecting heat transfer can be separated into three main areas: 1) fluidizing media, 2) particle bed, and 3) heater and tube assembly.

-Fluidizing media-

It has been shown by many investigators, including Davidson (2), Leva, et al, and Bartel, that the flowrate of the fluidizing gas has a pronounced effect on heat transfer coefficient. Depending upon the type and size of particles used, the heat transfer coefficient may increase monotonically, decrease monotonically, or pass through a maximum. These differences can be attributed to two opposing mechanisms occurring simultaneously. At lower flowrates, increasing the gas velocity enhances particle movement. This, in turn, increases the heat transfer coefficient. If the gas flowrate is increased further, the bed expands more, lowering the particle fraction. With fewer particles near the heaters, the heat transfer decreases.

This effect is determined somewhat by the particle size, and the point at which minimum fluidization occurs. That is, with large particles (0.015 inch diameter), the heat transfer coefficient decreases with increased velocity. With smaller particles (0.10 inch diameter), there is a maximum coefficient.

The other primary factor of the fluidizing gas, is the thermal conductivity of the gas. Ziegler, et al and Davidson, showed that increased thermal conductivity enhances the heat transfer. The density of the fluidizing media also has some affect

-Particle Bed-

Several investigators, Davidson, Leva, et al, and Ziegler, et al, have shown that there are three major particle parameters which effect heat transfer in a fluidized bed. They are particle diameter, solids heat capacity, and particle shape.

Smaller particles have higher heat transfer coefficients in general. As particle size decreases, more particles can get into the heated region of the heaters. The additional area promotes heat transfer. This effect decreases at very small particles diameters (less than 0.01 inch).

The second effect, that of heat capacity, can also be explained. If more heat can be stored in a particle, then the heat transfer should be increased.

According to Bartel, particle shape can decrease the heat transfer coefficient, by reducing the overall surface area. Although the more jagged particles have more surface area per particle than spherical glass beads, the rough shaped particles can pack more closely together than can the spheres. Thus, the overall surface area is reduced.

Thermal conductivity and density of the solid particles does not seem to have an effect on the heat transfer. According to Davidson, the bed height also has little effect if the bed is more than a few centimeters high.

-Heater and Tube Assembly-

Two major factors have been found to have influence on heat transfer. Davidson suggests that the tube diameter has an effect for diameters increasing from about 0.1 mm to about 1 cm. Larger diameters, seem not to have any affect on heat transfer.

Also, according to Davidson, heat transfer can vary with angular position around a tube, because of the dynamics of flow around a horizontal cylinder in a fluidized bed. As shown in Figure 2, a stagnant cap of particles forms on top of the tube. In this cap, the particle motion is much less than in the bulk phase. On the bottom of the tube, a thin gas film forms, into which few particles can penetrate. The top and bottom of the tube are then effectively insulated and will have higher surface temperatures than will the sides of the tubes, where fluidization is much better. This higher temperature will cause lower coefficients to be observed on the top and bottom than on the sides. It is therefore important to locate the thermocouple in the same angular position on the tube for all experimental runs, to measure uniform heat transfer coefficients.

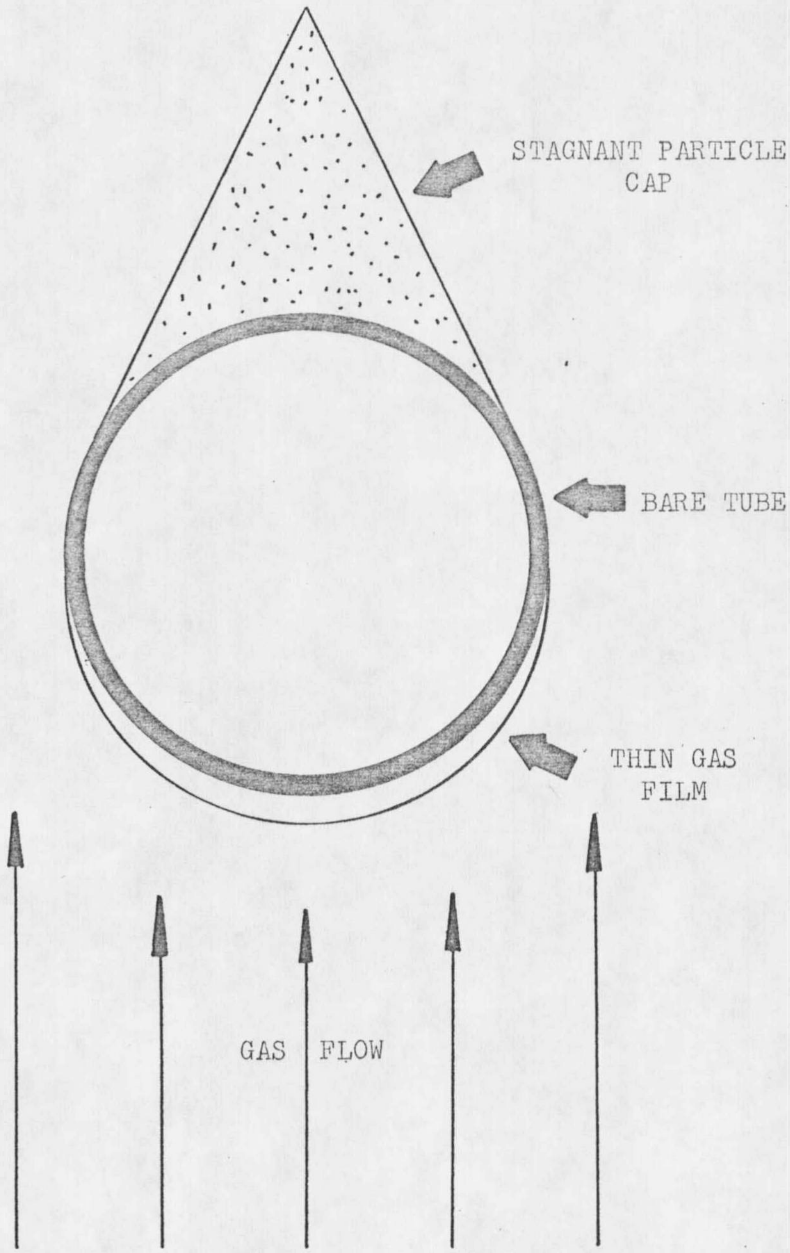

Figure 2. Bed Dynamics Around a Bare Tube

EXPERIMENTAL WORK

Objectives of This Study

This study was divided into two parts: 1) to determine the change in heat transfer coefficient with respect to the number of tubes in a horizontal tube bundle, and 2) to determine the effect of heater position in a 19 tube bundle. In addition, the air mass velocity was varied to obtain data on both sides of the maximum heat transfer as mentioned earlier. Preliminary runs were made to calibrate the instruments, and to determine if particle size had any effect other than that already mentioned.

Briefly then, the following experimental parameters were used in this investigation:

-Fluidizing Media: air, entering at room temperature. The inlet properties were assumed to be fairly constant.

-Bed Particles: spherical glass beads, manufactured by Minnesota Mining and Manufacturing Company. The final diameter selected was 0.011 inch, though, for preliminary runs, 0.008, and 0.0185 inch glass beads were also used.

-Tubes: carbon steel tubes, 5/8" outside diameter. Tubes in a bundle were located symmetrically about a center tube. Bundles of 1,7, and 19 tubes were used.

-Heat Input: Two different levels of heat input were used as follows: 1) single tubes and very low flowrates - 100-105 watts, 2) tube bundles - 150-160 watts. The variations at each level were caused by inherent differences in the various heaters.

Experimental Equipment

The equipment used in this study, can be separated into three sections: 1) fluidizing column and air supply, 2) heater and tube assembly, and 3) related equipment.

-Fluidizing Column and Air Supply-

Figures 3,4,and 5 show the fluidizing column employed in this study. It was a rectangular column, 7.5 feet high, with inside dimensions of 14" by 6.625". It was constructed of 0.75" Plexiglas, and fastened together with screws and solvent to prevent air and particle leakage.

The top consisted of two pieces of Plexiglas with five 2" diameter holes in each. Sandwiched between the two pieces was 140 mesh brass wire cloth and a rubber gasket to prevent particle leakage. In all four sides at the top of the column, was another hole, 3" in diameter, with brass wire cloth covering them.

The distributor plate was constructed of two 1/8" steel plates perforated with 1/8" holes. Again, sandwiched between the plates, was brass wire cloth and a rubber gasket.

Two micarta plates, 15.5" by 18", were placed on opposite sides of the column, 5" above the distributor plate. In the front plate, 5/8" holes were drilled through to let the heaters pass through. At the corresponding points in the opposite plate, 1/2" holes were drilled in 0.4" to accomodate the insulated ends of the heaters.

Air was pumped to the column from a Sutorbilt Blower run by a 7 1/2 Hp motor. Two valves, a main line valve and a bypass valve, were used to adjust the flowrate of air. To cut down on vibration, a section of rubber hose connected the steel pipe from the blower to the column. Eight stainless steel tubes located below the distributor plate, and perpendicular to the air flow, were used to straighten the flow as it entered the column.

-Tube and Heater Assembly-

Bare, carbon steel tubes with 5/8" outside diameter were used. A detailed drawing is given in Figure 6.

The heaters were Firerod cartridge electric heaters manufactured by Watlow Electric Manufacturing. They have a 6.5" heated section, and insulated ends of 0.4" and 3". The leads were connected through a Simpson wattmeter and a rheostat, to a 110 volt A.C. outlet. For runs in which a lower heat input was desired, a Variac was connected in the line. The Variac was used in some cases to maintain the input voltage, and at other times to prevent overheating in the column.

The blower described earlier, operated with a magnetic switch. Since it was necessary to have the blower on if the heaters were on, a safety switch for the heaters was connected through the blower switch. Thus, if the blower was accidentally shut off, the heaters would also shut off. A heater is shown in detail in Figure 7.

To promote contact between the tube and heater, the heater was coated with copper antisieze compound before inserting the heater into the tube.

An iron-constantan thermocouple was attached to each tube. Each thermocouple, located at the midpoint of the tube, was embedded 1/16" into the tube and silver soldered into place. Each thermocouple was checked before final assembly. The thermocouple wire was then passed out through a 1/16" diameter hole bored longitudinally in the 3" insulated end of the heater. This is shown in Figure 8.

-Related Equipment-

A thermocouple was located inside each of three, 1/16" diameter copper tubes. These tubes were located at three positions in the column to record the temperature at the top, bottom, and middle of the bed. The tubes were passed through the side of column. All the temperatures, both the tubes and bed, were recorded on a Honeywell Brown Elektronic chart recorder.

Two manometers were included in the system: one measured the pressure drop across an orifice in the main air line. It was used to determine the air mass velocity to the column. Backpressure from the column was accounted for with a Duraguage pressure guage. The other manometer measured the pressure drop across the tube bundle. Copper tubes, similar to those used for the bed thermocouples, were used for the pressure taps. The thermocouples and pressure taps in the bed are shown in Figure 9.